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RESEARCH ARTICLE

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The coordination of eye, head, and hand movements in a natural task

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Abstract Relatively little is known about movements of the eyes, head, and hands in natural tasks. Normal behavior requires spatial and temporal coordination of the movements in more complex circumstances than are typically studied, and usually provides the opportunity for motor planning. Previous studies of natural tasks have indicated that the parameters of eye and head movements are set by global task constraints. In this experiment, we explore the temporal coordination of eye, head, and hand movements while subjects performed a simple block-copying task. The task involved fixations to gather information about the pattern, as well as visually guided hand movements to pick up and place blocks. Subjects used rhythmic patterns of eye, head, and hand movements in a fixed temporal sequence or coordinative structure. However, the pattern varied according to the immediate task context. Coordination was maintained by delaying the hand movements until the eye was available for guiding the movement. This suggests that observers maintain coordination by setting up a temporary, task-specific synergy between the eye and hand. Head movements displayed considerable flexibility and frequently diverged from the gaze change, appearing instead to be linked to the hand trajectories. This indicates that the coordination of eye and head in gaze changes is usually the consequence of a synergistic linkage rather than an obligatory one. These temporary synergies simplify the coordination problem by reducing the number of control variables, and consequently the attentional demands, necessary for the task.

Keywords Eye, head, hand coordination · Natural tasks · Saccadic eye movements · Human

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Introduction

In natural circumstances, the eye, head, and hand are in continual motion in the context of ongoing behavior. This requires the coordination of these movements in both time and space. However, we know relatively little about the nature of these movements and their coordination in ordinary behavior. Studies of eye, head, and hand movements have typically been with single movements, usually to flashed stimuli. But the general problem is much more difficult. Eye, head, and hand all need to act with respect to a common coordinate system and remain synchronized in time across multiple actions. Stimuli in normal environments do not usually appear suddenly and evoke reactive movements. Much of the time, stimuli become targets by virtue of their role in ongoing behavior. The reduction in temporal and spatial uncertainty afforded by the continuous presence of stimuli in ordinary behavior allows for motor planning, and for the use of spatial memory in targeting. This may change many characteristics of the responses, particularly their temporal coordination. For example, the latency of hand movements relative to the eye is reduced when the target is continuously visible (Abrams et al. 1990). The latency of head movements is also affected by the predictability of the target (Fuller 1992). Evidence for the use of spatial memory in targeting eye and hand movements is provided by the work of Epelboim et al. (1995b), who showed substantial reduction in the time required to tap a sequence of lights as the task was repeated.

Another aspect of the target selection process in ordinary behavior is the demand placed on attentional mechanisms. The evidence suggests that each targeted movement requires a shift of attention to the target location. This has been demonstrated in the case of saccadic eye movements by Kowler et al. (1995), Deubel and Schneider (1996), and McPeek et al. (1999). In addition, Frens and Erkelens (1991) have found that eye-hand coordination could be disrupted by an auditory distractor presented at the initiation of the reaching movement, indicating the need for central attentional control of the coordinated movement. A central role for attention in target selection is also manifest in the behavior of cells in the lateral intraparietal area of the posterior parietal cortex. The activity of cells in this region is modulated by the behavioral relevance of a target (Andersen et al. 1997). When targets are continuously visible, a stimulus brought into a receptive field by a saccade will evoke a response only when the stimulus is behaviorally relevant (Gottlieb et al. 1998). In ordinary behavior, the attentional demands of each action may place constraints on the sequencing of the movements. The observer also needs to interleave other visual operations such as acquisition of information about object properties.

A related issue that arises in natural behavior is that properties of the movements are influenced by the particular task. For example, Epelboim et al. (1995b) show that the accuracy and duration of the fixations depend on whether the observer is tapping a set of lights or is simply instructed to look at them. In addition, peak gaze velocities are higher for tapping than looking, suggesting task-dependent modulation of the gain of the vestibular ocular reflex (Epelboim et al. 1997). The residual retinal image motion caused by the head movement, and not completely compensated by the vestibular ocular reflex, is also greater when tapping (Epelboim 1998). This suggests that tapping accuracy is robust to retinal image motion and that observers naturally adjust the speed of the movements to take advantage of the minimum requirements of the tapping task. Thus we might expect that the full range of possible eye, head, and hand coordination patterns requires observation of performance in a variety of different real-world tasks.

The goal of the present paper was to extend the previous investigations and examine the characteristics of unrestrained eye, head, and hand movements in a different real-world task. We examined performance in a simple visuomotor task, involving copying a pattern of colored blocks, in conditions where the eye and head were free to move together and real objects were manipulated. The task was made up of identifiable subtasks: information-gathering eye and head movements and the visually guided, coordinated actions of the eye, head, and hand. These simple behaviors are components of many everyday sensory motor tasks. With the exception of Land et al.'s (1999) investigation of tea-making, previous investigations of natural tasks have focused on eye-head coordination. In the present investigation, we focused in particular on the temporal coordination of the eye and hand as well as eye and head. We asked how eye, head, hand coordination is maintained across an extended behavioral sequence. We also asked whether the continuous presence of the stimulus array affects the coordination pattern, given the opportunity for the use of motor planning and spatial memory in programming the movements, and how the coordination pattern might be affected by the demands of the specific task. We found that observers set up temporary, task-specific synergies or coordinative structures (Turvey et al. 1991) to maintain eye, head, hand coordination. This not only has the advantage for controlling coordination, but also makes economical use of attentional resources. As in the work of Epelboim and colleagues (1997), the kinematic parameters of the movements appear to be set by global task strategies. We also find that the relationship between the eye and head is more flexible than previously reported (some aspects of this finding have been reported by Smeets et al., 1996). and more likely to accompany gaze shifts for the purpose of guiding hand movements than for information gathering.

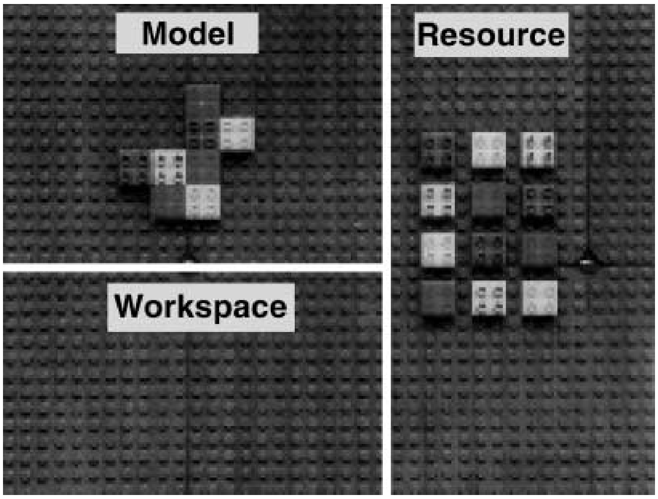

Fig. 1 Layout of experimental working plane containing the Model, Resource, and Workspace. The board subtended approximately 80°×60° of visual angle, and was set at 10° from vertical. Each block subtended approximately 2.25°

Methods

Task

We used a head-mounted eye tracker system that allowed us to monitor unrestricted head movements as well as eye movements. Hand position was also monitored. In this paradigm, observers make a sequence of reaching movements to pick up and place colored blocks in the same position as a nearby model configuration. The layout of the task is shown in Fig. 1. Subjects pick up blocks from the "Resource" area, and place them in the "Workspace" area, in the same configuration as those in the "Model" area. The Model area contained an eight-block pattern to be duplicated, the Resource area contained twelve blocks from which blocks could be selected to construct the copy, and the subject was instructed to build the copy in the Workspace. The task is described in more detail by Ballard et al. (1995).

Monitoring eye position

Monocular (left) eye position was monitored with an Applied Science Laboratories model E4000SU eyetracker (ASL). This is a headband-mounted, video-based, IR reflection eyetracker. The eye position signal was sampled at 60 Hz and had a real-time delay of 50 ms. The accuracy of the ASL's eye-in-head signal is approximately 1° over a central 40° field. The ASL tracks both pupil and first Purkinje image centroids, and calculates horizontal and vertical eye-in-head position based on the vector difference between the two centroids. This technique reduces artifacts due to any movement of the headband with respect to the head. Errors in reported eye position caused by movement of the headband with respect to the head were less than 0.1°, measured over a sequence of movements at a peak velocity of 60°/s[1] (this was more than the peak head velocities observed in the experiment). Gaze position (integrated eye-in-head and head-position and orientation) is calculated by the ASL using the eye-in-head signal and a head position/orientation signal from a 6-degrees-of-freedom magnetic field head-tracking system (Ascension Technology). The ASL reports gaze position as the *x-y* intersection of the line-of-sight with the working surface, whose position and orientation are entered into the ASL during calibration. Eye-in-head, head orientation and position, and gaze intercept are available on an RS-232C serial interface from the ASL. The digital data stream was collected on an Apple Macintosh 840AV computer for storage and analysis. The ASL also provides a video record of eye position. The headband holds a miniature "scene-camera" to the left of the subject's head, aimed at the scene. The ASL creates a crosshair overlay indicating eye-in-head position that is merged with the video from the scene-camera, providing a video record of the scene from the subject's perspective on the scene-monitor, along with a crosshair indicating the intersection of the subject's gaze with the working plane (see Fig. 1). Because the scene-camera moves with the head, the eye-in-head signal indicates the gaze point with respect to the world. Head movements appear on the record as full-field image motion.[2] The ASL was calibrated for each subject before each trial session. For calibration, the subject was fitted with a biteboard and seated a comfortable distance from the work surface, typically 60–75 cm. At this distance, the blocks subtended about 2.5° visual angle. (Because of the nature of the calibration routine, unintentional movement of the head during calibration would introduce errors. Following calibration, the head was free to move during the experimental trials.) Calibration was performed over a region of about 25° by 20° and is described in detail by Pelz, 1995).[3]

Monitoring head and hand position

Position and orientation of the head was measured with an Ascension Technologies magnetic field tracker, attached to the eyetracker's headband. The transmitter unit was mounted above and in front of the subject's head. The position of the sensor is reported as the (*x, y, z*)-position with respect to the transmitter, and orientation as azimuth, elevation, and roll angles. Distances (*x, y, z*) are scaled from –36 inches to 36 inches, yielding a precision of 0.001 inch (0.003 cm). Orientation angles (azimuth, elevation, and roll) are scaled from –180° to 180°, with a precision of 0.005°. Absolute error was less than 0.2±0.2 cm when the receiver was within 40 cm of the transmitter. In these experiments, the head was positioned 30 cm from the transmitter and was typically within this range. (Errors reached approximately 1.0±0.3 cm at a distance of 65 cm.) Orientation values (computed based on the relative strength of the three channels) are less sensitive to distance. Errors were below 10 min arc, and unaffected by distance out to 65 cm. Further details are given by Pelz (1995). A second similar magnetic unit (Polhemus Fastrak) was used to track the hand movements. The 1.5×2.5 cm receiver was taped to the subject's thumb. Thumb position reflects both arm and hand movements. We used the thumb rather than the wrist in this experiment in order to give a better indication of contact with the board for block pickup and placement. For simplicity, we refer to this as "hand" position. The transmitter for the hand tracker unit was placed behind the board, so that the distance between transmitter and receiver was minimized and the noise level reduced. The hand position data were sent via a serial connection to the lab computer. The temporal resolution of head and hand signals was 125 Hz, with a real-time delay of 8 ms. The head position data were reported directly to the ASL's PC, where it was integrated with the eye position signal to calculate the integrated gaze position. The raw head position signal was also sent to the Macintosh lab computer, where it was logged along with gaze, eye, and hand movement signals. During each trial, the lab computer read eye, head, and gaze position from the ASL, hand position from the Fastrack, and the video timecode from the VCR. A Sony EVO-9650A Hi-8 video deck was used to record the video from the scene camera with gaze position overlay. The video deck could be controlled automatically by the computer, allowing the data stream and video record to be correlated.

Procedure

Following calibration, the subject was instructed to duplicate the pattern as quickly as possible without making errors, using one hand (of the subject's choice), but was otherwise free to choose any strategy and sequence of movements to accomplish the task. Ten subjects performed the basic block-copying task, completing from 8 to 26 different patterns, each consisting of eight blocks. The eyetracker was calibrated at the beginning of each block of trials, and calibration offset of a central fixation point was checked just before each trial began. The calibration was recentered if it was in error by more than 0.25°, which occurred on less than 20% of the trials. The full-field calibration was checked at the end of each block of trials and the data were discarded if the calibration varied by more than 1°, less than half the subtense of a single block. This occurred for only two blocks of trials. Thus, in general, the calibrations were very stable.

Block-move strategies

The sequential nature of the task makes it convenient to break up the sequence of movements into "block moves." Each block move begins when the previous block has been placed in the Workspace and the eyes move away from that area. It ends when the present block is placed in the Workspace. Each block move is made up of a set of lower-level subtasks; the subject must find (or remember) the color and position of the block to be moved, move the hand to "pick up" a block of the same color in the Resource area, then return to the Workspace to "drop" the block to the correct position in the duplicate being constructed. The gaze- and hand-movement "primitives" making up each block move were used to describe the subjects' strategies. Gaze changes are labeled by the areas in which fixations occur: M for a fixation in the Model area, P for the fixation required for picking up a block in the Resource, and D for the fixation in the Workspace for putdown. P and D are also used to label the corresponding hand movements. By reviewing the videotaped records in slow motion, the sequence of fixations and hand movements used to copy each block was used to label the strategy used for that block. Figure 2 shows four typical block-move sequences schematically. In the most frequent strategy, the eye makes two fixations on the Model. Gaze moves first to the

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[1] To estimate slippage, the relative movement was measured between two projected laser points, one on the headband and one on a bite bar in the subject's mouth. This was translated into eye position error by imposing headband movements while the subject maintained fixation on a point, with the head fixed.

[2] Because the scene camera is not coaxial with the line of sight, calibration of the video signal is strictly correct for only a single distance. All gaze points are in the plane of the working board, and subjects typically do not change their distance from the board substantially, so the parallax error is not significant in this task, though it can be significant in tasks not constrained to a near-vertical plane. The eye-in-space signal is calculated by the ASL, by integrating the eye-in-head and head position/orientation signals and is not affected by parallax.

[3] The calibration can be performed with 9 or 17 points. The 17-point calibration target increases accuracy by allowing the target points to cover a larger area while reducing the area over which eye-position data must be interpolated. The 17-point target is especially critical when the scene-camera is fitted with a wide-angle lens that suffers from barrel distortion.

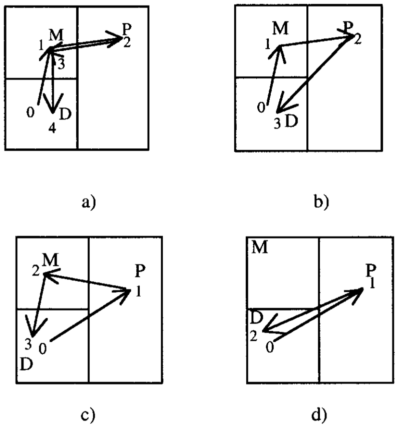


Fig. 2a–d Sequences of gaze changes making up **a** an *MPMD* block move, **b** a *MPD* move, **c** a *PMD* move, and **d** a *PD* move. (*M* Model fixation, *P* pick up a block in the Resource, *D* drop, or placement of a block in the Workspace)

Model area, then to the Resource to guide pickup. Gaze then returns to the Model, and then to the Workspace, where the block is dropped in position. The block move is thus labeled as an “MPMD” sequence. Previous work has shown that approximately 90% of block moves can be classified as one of the four types in Fig. 2, labeled MPMD, MPD, PMD, and PD. Block moves were categorized as “more than MPMD” sequences if the subject looked more than twice into the Model area during a single block move. A small number of block moves (3.3% across ten subjects) still did not fit into any of the above categories and were labeled “other.” These were typically block moves in which the subject had difficulty picking up or placing a block, or in which the subject made an error. The mean number of Model references per block copied was 1.5, indicating frequent references to the Model, rather than using visual memory. This aspect of the task is described more fully by Ballard et al. (1995) and Pelz (1995).

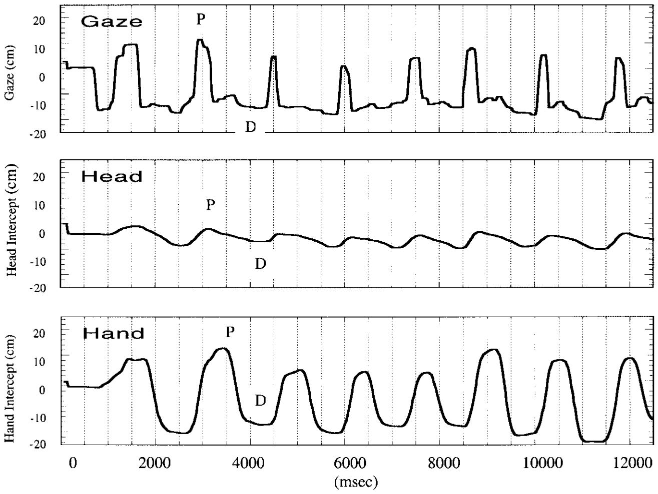


Fig. 3 Example 12-s segment of gaze, head, and hand movements during the block-copying task. Horizontal components only are shown. *Positive values* denote the Resource (pickup) area on the right, and *negative values* indicate the Model and Workspace (drop) areas on the left. The hand moves back and forth between pickup and drop. Model fixations are interposed between pickup and drop. These are not very obvious in the *horizontal trace*, but are indicated by the longer gaze durations on the *left*, and the slower head velocities on the leftward movement

Results

A striking aspect of task performance is the regular, rhythmic pattern of eye, head, and hand movements observed while subjects copy the block pattern. Figure 3 shows the horizontal components of gaze, head, and hand movements during a 12-s segment of a trial. The hand is moving back and forth between pickup in the Resource (positive values) and dropping the block in the Workspace (negative values). Gaze and head similarly go back and forth between Resource and Workspace, with a movement to the Model (negative values) interposed on the return movement. Each of these components follows a cyclical pattern that repeats every 1.5 s, with approximately constant phase relations. This reflects the repetitive action of picking up and placing each block in the copy. The basic coordination of the movements is accomplished by maintaining the same pattern of movements for each block, with the eye leading, followed by the head, and then the hand. In order to give a rough measure of the time-locked and repetitive nature of the different movements, a cross-correlation of the waveforms was performed for all the data. Peak correlations ranged from 0.7 to 0.8, for four subjects, reflecting the stability of this basic relationship. The regularity of these patterns is not likely to be a result of overtraining, as it is observed on the first trial, and performance remains stable across trials. Although there is undoubtedly some learning of the spatial layout, the task itself does not require any particular training, and only a relatively small number of trials were performed.

Eye and hand coordination

A more detailed analysis of the relative latencies reveals consistent patterns that vary with the particular strategy used for copying a given block. The individual block moves were classified into the four basic strategies described above, beginning with the first fixation following placement of the previous block in the copy. The beginning and end of the movements from one region to another were then found for all the trials within a given category for the eye, head, and hand. The criterion for reliably detecting a head or hand movement was approximately 10% of the peak velocity (that is, ~2°/s for the head and ~10 cm/s for the hand). The mean arrival and departure times for these transitions are shown in Fig. 4 averaged over five subjects. Figure 4a plots the data for the MPMD trials. The PMD and MPD trials are shown in Fig. 4b and c. Time is plotted on the *x*-axis. The top row is for the head, the middle row for gaze, and the bottom row for the hand. At the beginning of the block move, the eye fixates the Model for about 300 ms, followed by a Resource fixation of 350 ms for pickup, a second 300 ms Model fixation, and then a 700 ms Work-

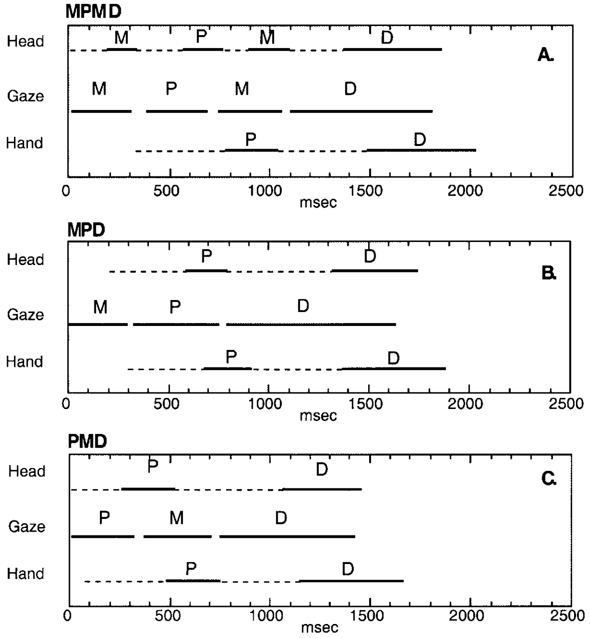
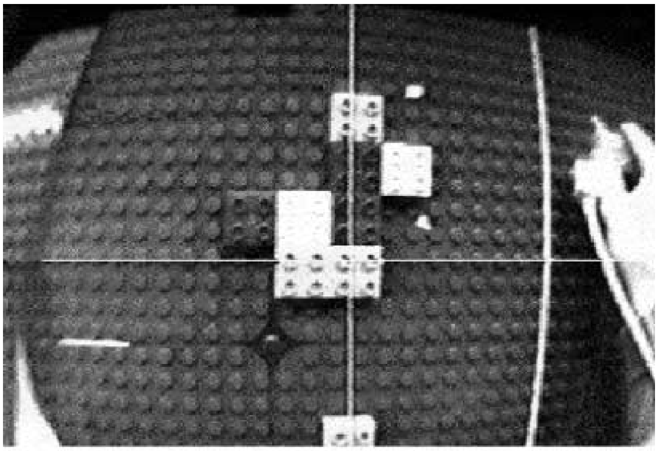


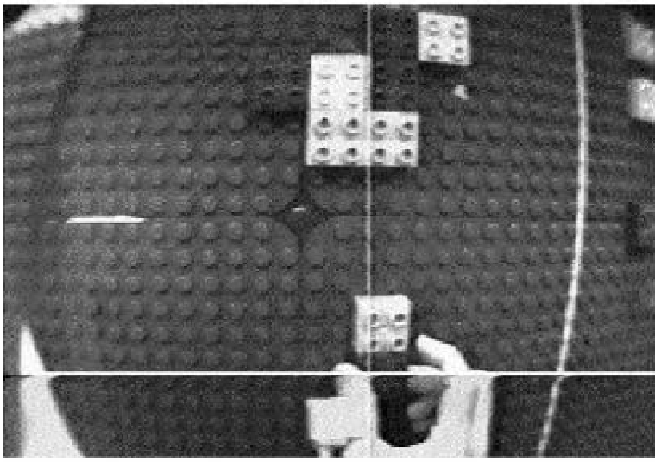
Fig. 4a–c Gaze, head, and hand movements for each strategy, averaged over five subjects. Time is shown on the *abscissa*. The *solid lines* denote the period when the gaze/head/hand was stationary. The area is indicated *above the line* (*M* Model, *P* pickup in Resource, *D* drop in Workspace). The *dashed lines* indicate when the hand/head is moving between areas. Between-subjects standard errors range between 14 and 113 ms (mean 55 ms) for the eye and the hand

space fixation for block placement. The head movements follow the same sequence, with shorter stationary periods because of the longer movement times. The hand alternates between the Resource and Workspace, with the pickup taking about 250 ms, and the drop about 500 ms. Note that the eye always arrives first, for the pickup and drop actions, followed by the head, and then the hand. This can be seen by comparing the start of the three solid lines marked P, and also the three lines marked D. The later arrival time of the head and hand is a consequence of the longer movement time. This is the stable repetitive pattern described above, in Fig. 3. The magnitude of the lead time varies with the strategy, however.

One prominent feature of performance is the difference in the pattern of eye and hand coordination between the pickup and drop events. While pickup and putdown are always initially guided by fixation on the target block, the eye departs much earlier before pickup, frequently before contact is made with the block. When a Model fixation is made before block placement (MPMD and PMD strategies, Fig. 4a, c), the eye departs from the block to be picked up 100–150 ms before the arrival of the hand. This is not true for the MPD strategy (Fig. 4b), where the eye remains on the target block for nearly 100 ms after contact before moving directly to guide placement. Figure 5a shows a frame from the video record of a typical pickup event. As the hand nears the selected block, but before the subject grasps the block and lifts it away from the board, the gaze returns to the Model area for the second Model fixation. In contrast, subjects usually maintain fixation on the block during a drop until the block is in place, as shown in Fig. 5b. Presumably, visual control of the final stage of the pickup is not needed. Thus subjects are very sensitive to the accuracy demands of the task, and dedicate visual resources to pickup only for as long as needed when a model fixation needs to be made after pickup.



a) Pickup



b) Drop

Fig. 5a, b Differences in eye/hand coordination for block pickup (**a**) and drop (**b**). In **a** gaze departs before pickup, just before the hand contacts the block. In **b** gaze is maintained until the block is placed on the board

The main feature of interest here is the comparison of eye-hand latencies for the initiation of the pickup and drop actions in the three strategies, where a simple structure emerges. Comparing the MPMD and PMD strategies in Fig. 4, the latter can be seen to be almost identical to the former, except for the initial Model fixation. That is, eye-hand latency in the PMD trials is similar to that in the (M)PMD trials except for the initial model fixation. Thus the hand leaves for the pickup in the Resource at

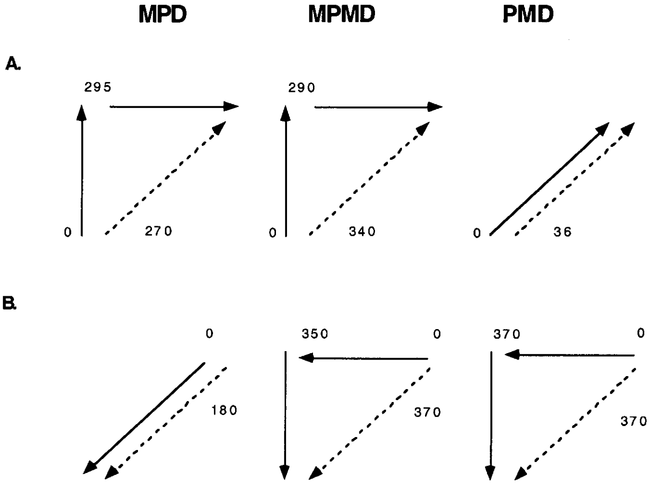


Fig. 6a, b Eye and hand latencies for the MPD, MPMD, and PMD strategies. **a** shows eye and hand movements to pickup a block at the beginning of a block move. The *solid lines* denote the eye movements, and the *dotted lines* denote the hand movements. The time the movement is initiated is shown at the *base of the arrow*. In the MPD and MPMD strategies, the eye goes first to the Model, then the eye and hand move to the Resource. In the PMD strategy, the eye goes directly to the Resource. **b** shows the eye and hand movements to place the block in the Workspace after pickup. In the MPD strategy, the eye and hand go directly to the Workspace. In the other strategies, the eye fixated first in the Model

about the same time as the eye does, with the eye coming from the Model and the hand from the Workspace. (Compare the time of the gaze transition from M to P with the beginning of the dashed hand trace in Fig. 4a.) This means that, in the MPMD strategy, the hand waits 340 ms until the eye completes the Model fixation and then initiates the movement at the point when the eye is available for guiding the pickup. This is shown in Fig. 6, which shows a schematic of the trajectory and time of the initial eye and hand movements for the three strategies. The spatial layout of the three regions in the figure is the same as in the experiment. For the PMD trial, eye and hand movements for pickup are initiated at about the same time, with the hand leaving about 36 ms after the eye. (See the beginning of the dashed hand trace in Fig. 4c.) However, in the MPMD trial the hand does not move until 340 ms after the beginning of the trial. At this point the Model fixation is complete, and the eye then moves to guide the pickup. The relative latency of eye and hand is about 50 ms for this movement, close to that in the PMD trial. The initial part of the MPD trial also shows the hand waiting until the eye is available (the latency is 270 ms from the beginning of the trial, and 25 ms before the eye movement for pickup.

A similar analysis can be applied to the return movement to guide the drop, as shown in Fig. 6b. Here, the timing of eye and hand in the first part of the MPMD and MPD sequences (the MP part) is similar, but now a second Model fixation must be interposed between the pickup and the drop for the MP(M)D strategy. This makes the trial longer overall.[4] Another effect is to delay the hand movement until the Model fixation is complete, so that the hand now leaves for the drop shortly after the eye does. This is 370 ms after the previous departure of the eye to the Model after pickup. In the MPD sequence, where eye and hand go directly to drop the block, the hand leaves only 180 ms after the eye. Thus the hand movement is delayed by about 200 ms (relative to the departure of the eye) when a Model fixation is interposed. This pattern is repeated in the PMD trials.

These plots are averaged over five subjects. The between-subjects standard errors range between 14 and 113 ms (mean 55 ms) for the eye and the hand. Within-subject standard errors are typically smaller, ~35 ms on average. Thus the overall timing pattern is quite reliable, particularly within subjects. Data for the individual subjects are shown in Fig. 7. The individual subjects differed systematically in terms of overall trial duration and the relative latencies of hand and eye. For example, the MPMD trials ranged from 1,700 to 2,400 ms for the five subjects, with the eye-hand latency ranging between –250 (JW) and +250 ms (KK) for MPMD trials, and between +300 (MS) and 0 ms (JW), for MPD trials. However the relationship between the different strategies described above holds true for individual subjects, that is, the hand movement is delayed when an extra model fixation is made.

Coordination of eye and head movements

Reports of the degree to which head movements contribute to gaze changes has varied widely (Bard et al. 1992). To measure the head movements in this task we calculated the root-mean-square (rms) variation in head orientation, a measure that represents the average behavior over the task[5] (the rms values are approximately 25% of the range). Figure 8 shows mean azimuth, elevation, and roll rms values for three subjects. The largest movements were in azimuth, where the rms value was ~2.5°. The rms for elevation was about 1°. A similar tendency for smaller vertical than horizontal movements has been observed by Glenn and Vilis (1992). The range of horizontal head movements was ~10°, or about two-thirds the size of the gaze shifts. The widest variation between subjects was found in the roll angle (ranging

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[4] The extra fixation takes about 350 ms. Part of this time cost is made up by the eye departing for the resource a little earlier (70 ms) in the MPMD strategy. Another part is made up by a shorter fixation in the workspace (140 ms).

[5] The rms measure, however, can be inflated by a change in the mean orientation of the head over the trial. This had to be taken into account because subjects typically displayed such mean orientation shifts as they progressed from the beginning of the model to the end. A regression line was fit to the recorded rotation about each axis and was subtracted from the raw orientation record before analysis. This correction lead to changes in the rms values of between 5 and 25%.

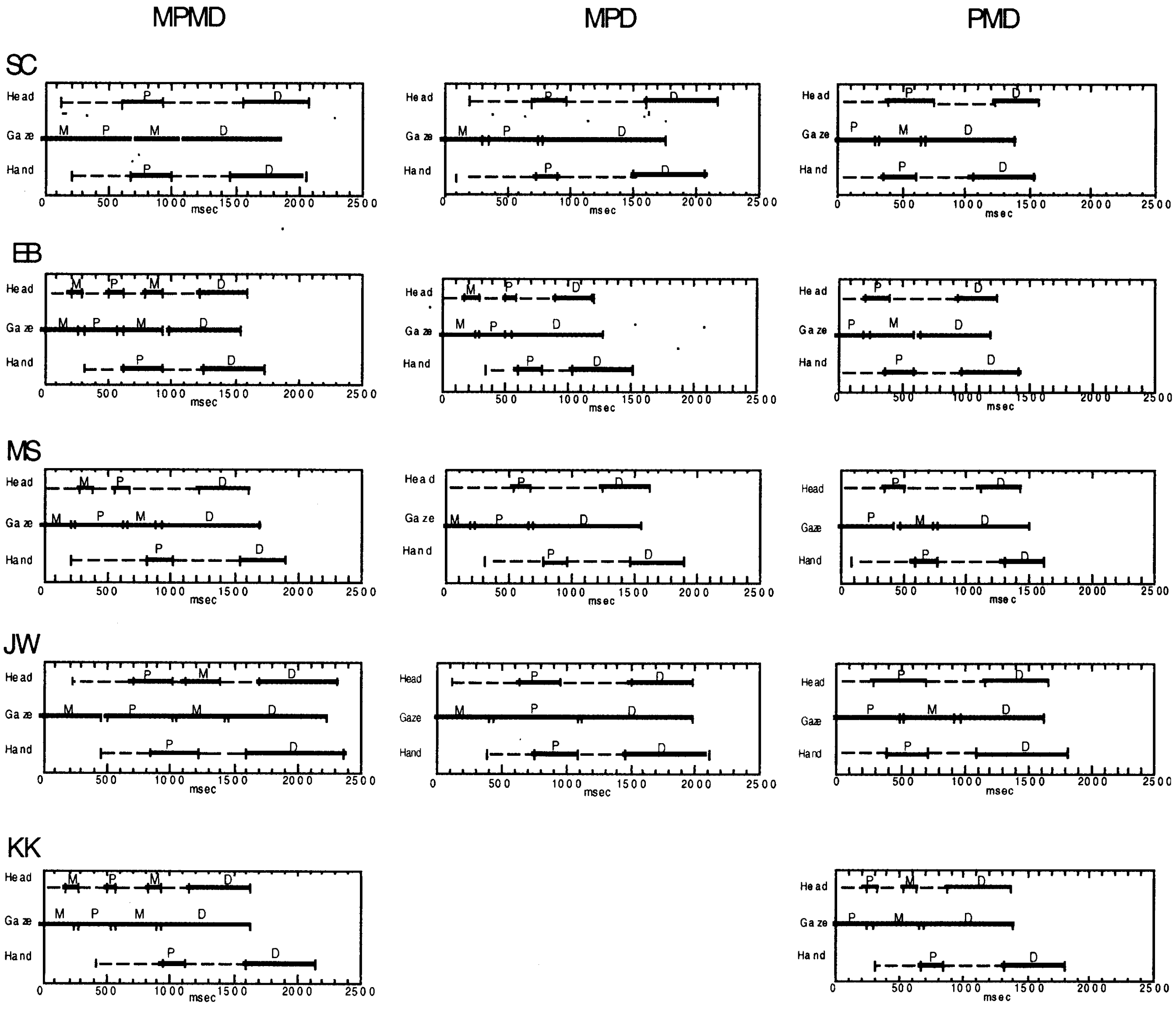

Fig. 7 Gaze, head, and hand movements for each strategy for five subjects, showing the range of coordination patterns between subjects. Standard errors for the start and end points of the movements (not shown for clarity) are 35 ms, on average

between ~1° and 2° rms). Substantial between-subject variability in head movement magnitude has been reported in the literature (Fuller 1992) and was also observed here. We also noted substantial variation in individual subjects' head movements from day to day. Peak velocities for the head varied widely both between and within observers, ranging between ~10 and 40°/s for rightward movements, and dropping to the range ~5 to 20°/s for movements back to the left before putdown. These values are comparable with those observed by Epelboim et al. (1997) in their tapping task. (The slower leftward movement is a consequence of the greater frequency of model fixations on the return movement, after pickup, than on the movement before pickup.).

Trajectories

Subjects primarily moved their head toward points that required careful manual manipulation, i.e., pickups and putdowns, but were less likely to move their head for Model references, possibly because those fixations are for information gathering, not to guide manipulation. In the series of fixations making up a PMD sequence (alone or as part of an MPMD sequence), the gaze moves from the Resource area to the Model, then on to the Workspace. The Resource to Model gaze change is primarily horizontal, and the Model to Workspace gaze change is primarily vertical. Because of the frequency of MPMD and PMD sequences, it is useful to examine gaze and head trajectories during the PMD sequence. Four subjects' gaze and head movement records were examined. The sections of each trial with a PMD sequence were isolated, and the concurrent head movements were analyzed to determine what head movements accompanied the gaze changes. Significant between- and within-subject

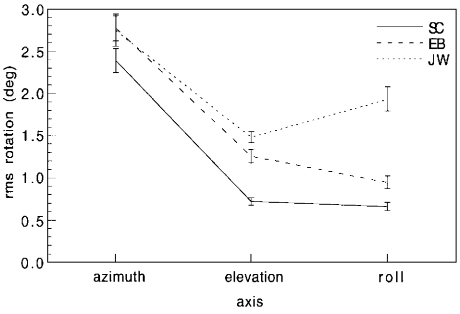

Fig. 8 Mean azimuth, elevation, and roll rms amplitudes for three subjects

variability was observed in the degree to which eye and head movements were linked. Subjects showed evidence of a dissociation of eye and head trajectories, with varying frequency and to varying degrees.

Three PMD sequences for subject E.B. are shown in Fig. 9. They are samples selected to illustrate the range of eye/head coordination observed in subjects performing the block-copying task. Figure 9a shows the subject executing a PMD sequence in which gaze and head are apparently executing coupled eye/head movements with common spatial and temporal patterns. On the left is a two-dimensional plot of the gaze intercept on the working plane as a block is picked up in the Resource area, gaze returns to the Model, then moves to the Workspace to guide the putdown. On the right is a two-dimensional plot of head orientation over the same period, at an expanded scale to show the head movements more clearly. The common goal of eye and head for each of the two gaze changes is evident in the plot of head position. The horizontal component of the head's motion is completed before the vertical component is initiated. Figure 9b shows another PMD sequence from the same subject, performed on the same day as that shown in Fig. 9a. It is clear from the plots that the eye and head are executing movements that were programmed to different targets. The eyes execute a sequential program, moving first to the Model, then to the Workspace, while the head executes a single, diagonal movement toward the Workspace in preparation for guiding the placement of the block. Figure 9c shows another PMD sequence for this subject. This case can be considered intermediate between the two discussed above. Here the head follows a curved trajectory from the Resource to the Workspace. The horizontal head movement is initiated first, but the vertical component begins before the horizontal movement is complete, causing a curved trajectory. Table 1 shows the relative frequencies of these three patterns for four subjects. Head movements were labeled as "Separate H & V" for block moves like that shown in Fig. 9a, "Diagonal" for cases like that shown in Fig. 9b, and "Curved" for cases like that shown in Fig. 9c. Block moves in which the vertical component of head motion was too small to meaningfully label the head movement into one of the above categories, and cases where eye and head movements could not be reliably paired were excluded. Note the wide variation between subjects. No diagonal head movements were observed for subject M.H., while S.C. made diagonal movements on 50% of the trials. Subjects E.B. and J.W. were intermediate between those extremes.

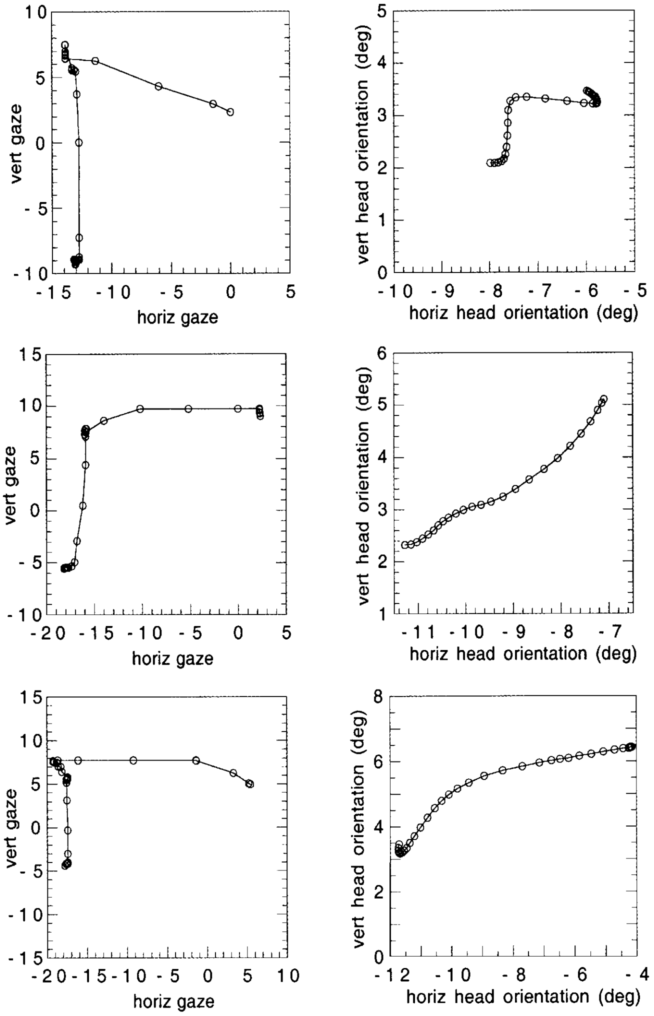

Fig. 9a–c Examples of different head trajectories from one subject. Gaze trajectories are on the *left*, and the corresponding head trajectories are on the *right*. **a** shows separate horizontal and vertical head movements; **b** shows a diagonal head trajectory; and **c** shows a curved head trajectory

Table 1 Relative frequency of head movement types for PMD sequences for four subjects (*H* horizontal, *V* vertical)

Head movement	EB	JW	MH	SC
Separate H & V	0.45	0.22	0.67	0.35
Diagonal	0.36	0.07	0.00	0.50
Curved	0.19	0.72	0.33	0.15

Latencies

The timing of the head movements relative to the eye is more complex than for the hand, since the head frequently does not follow the eye to the Model. The head movements are shown in the top trace in Fig. 4. When the head does not go to the model, as shown in Fig. 4b and c, the head behaves like the hand. That is, head movements are typically delayed when an additional model fixation is made, just as the hand is. However, whereas the hand movement is not initiated until after the eye, the head movement may precede it. This can be seen in Fig. 4c, where the head begins the movement to the Workspace 100–200 ms before the eye does. The other difference between the hand and the head is that the head frequently goes to the Model with the eye. This occurs primarily in the MPMD strategy, as shown in Fig. 4a. When it does, the eye and head begin to move at about the same time.

Discussion

Subjects adopted a regular, rhythmic pattern of eye, head, and hand movements while performing the block-copying task. It was the essentially fixed relationship between eye, head, and hand, modulated by the different strategies, that underlay the regular pattern described in Figs. 3 and 4. Thus the temporal coordination of the eye, head, and hand was partly achieved by repetition of this fixed temporal pattern. The repeated cycle of the eye, head, and hand movements for each block appeared to act as a “coordinative structure,” which reflected the influence of both the intrinsic dynamics of the component movements and the task demands. The existence of these coordinative structures has been postulated by Turvey and others as a means of reducing the degrees of freedom associated with motor tasks (Turvey et al. 1991). This concept has typically been used to describe tasks such as oscillating the fingers on the left and right hands, where the two fingers tend to move in phase. The present results show that the concept can usefully be extended to the emergent temporal structure of natural behavior. Such coordinative structures may play the role of the central “clock” sometimes postulated to underlie the coordination of different movements (see Kowler et al. 1992 for a discussion). In our study, the task specified the single block cycle, with the hand alternating between pickup and putdown, and the eye alternating between information acquisition and hand-targeting and control. The overall duration of the cycle reflected the dynamics of the arm and the time required for block placement. The eye fixations were also a limiting factor in this task, since the hand appeared to wait for the availability of the eye when an extra model fixation was required. Consistent individual differences were observed in the overall cycle time, as well as in the relative latencies of the movements. The regularity of the timing patterns within observers (standard errors were about 35 ms) suggests that observers took advantage of the opportunity for motor planning to regulate the coordination of the eye, head, and hand. The observation of this opportunistic coordinative structure is consistent with the findings of Epelboim and colleagues (Epelboim et al. 1995a, 1997; Epelboim 1998) that observers set the parameters of the movements to satisfy global task constraints.

Eye-hand coordination

The underlying regularity in the movements varied with the specific sub-task being performed. Analysis of the way that the particular strategies affected eye-hand coordination revealed that the sequence of fixations controlled the timing of the hand and head movements. Thus in addition to the underlying temporal regularity, an important part of the temporal coordination was controlled by the availability of the eye. Vision was required for multiple purposes: gathering information about the color and location of the blocks in the pattern, interleaved with targeting saccades, and targeting and control of the hand movements. When eye and hand both went directly to the Resource for a pickup, the hand began to move about 30 ms after the eye. When the eye had to first make a Model fixation, the initiation of the hand movement was delayed for about 300 ms until the Model fixation was complete. A similar situation held for the return movement for putdown. The hand waited about 200 ms for the eye, and began the movement from the Resource at the time the eye departed from the Model. Thus eye-hand coordination appeared to be regulated by immediate availability of the eye. The hand might have waited for the eye either for target selection, or for visual guidance of the final part of the reach, or both. Target selection may have been difficult for a hand movement from one nonfoveated location to another. Alternatively, programming the movement might have required the allocation of attention, and this may not have been available when the eye was acquiring information from the Model pattern. Thus the demands of central attentional processes may regulate the coordination of eye and hand. The other constraint was that fixation was required in the Workspace for guiding the final phase of the reach and for attaching the block to the board. The hand movement took about 400–450 ms, and the eye movement was usually initiated at about the same time as the hand, so most of the reach was visually guided. Given that the Resource and Workspace locations were well known to the observer, the ballistic phase of the hand movement could in principle have been initiated without foveal guidance. This suggests that it is the need for visual guidance of pickup and putdown that is the primary factor here. Epelboim et al. (1995b) also note the need for visual guidance in their tapping task. Given that visual guidance is required, initiating the eye and hand together is an efficient strategy for maintaining coordination. The eye and hand can be linked as a temporary synergy or coordinative structure, where eye and hand are launched together, to ensure that the eye is available at the right time. This removes the need for a separate decision to initiate the hand movement independently of the eye. This reduction of the number of degrees of freedom, or number of variables that need to be controlled, is important because of the attentional demands of even simple movements.

Eye-hand latency varied over about 300 ms for different task contexts for a single observer, and over about 500–600 ms across the different subjects. In one subject, the hand led the eye by about 250 ms. This variation in latencies is substantially greater than is observed with single movements, where the eye typically leads the hand by 100 ms or less for targets with an abrupt onset, or lags by under 100 ms for continuously visible targets. (Abrams et al. 1990). Performance was also somewhat different from that observed by Land et al. (1999) while subjects made a pot of tea. In this context, the eye movement leads the initiation of the hand movement by about 560 ms (ranging between 430 and 680 ms for different subjects). It is possible that the longer latencies in their task reflects the greater opportunity for planning in the block-copying task. In the tea making, subjects frequently required whole-body movements to bring the target into view, and the task does not involve repeated actions. The relatively long latency of the hand movements might reflect the greater attentional demands of the ongoing complex task. In the block-copying task, the near-zero latencies (on average) may reflect the planning advantage afforded by the repetitive action. Even in single-trial experiments where the stimulus has a sudden onset, subjects can take advantage of the repetitive trial structure of the experiment to plan the reach.

Another manifestation of the regulation of eye-hand coordination by the specific task requirements was observed in the difference between pickup and putdown actions. When picking up a block in the Resource, gaze was typically held on the block targeted for pickup only until the fingers were about to touch the block. When the block was being placed in the Workspace, however, gaze was usually maintained until the drop was complete. Thus the pickup action could be completed using proprioceptive information alone, whereas putdown required visual control in addition, probably for orienting the block properly with respect to the board. The early departure of the eye from the pickup target, even before contact, suggests that subjects were already planning the next saccade to the Model during the hand movement to the Resource. It also shows that observers adjusted fixation durations and eye-hand coordination to take advantage of less-stringent accuracy requirements of the particular action. This is similar to the observations of Epelboim et al. (1997; Epelboim 1998), who has shown that the pattern of eye and head movements are different for tapping versus looking. When tapping, peak gaze velocities are greater, the head fails to stop completely for tapping as it does when looking, and the residual retinal image velocities are as high as 5/s. Thus subjects modulated the kinematics of the gaze sequence to match the accuracy requirements of the particular task.

Eye-head coordination

Head movements of variable amplitude, velocity, and latency accompanied the eye movements in this task. In general, head movements ranged between approximately 1° and 10° for gaze changes of 15°, although this varied substantially between subjects and even for the same subject on different occasions. Large intersubject variability in the magnitude of head movements in head-free subjects has also been observed by Borel et al. (1994). However, subjects invariably move their heads to some extent. In this respect our findings are consistent with those of Kowler et al. (1992), who found head movements accompanying even the small gaze changes during reading. This differs from other studies (Fuller 1992), where head movements were not a regular feature of gaze shifts until approximately 20°. It also appears to differ from nonhuman primates, where head movements do not appear until gaze changes of over 20° are made (Freedman et al. 1996; Fuller 1992). The present data suggest that, at least in humans, this property of gaze shifts is not reliable. The magnitude of the head movement is proably a function of the particular constraints of the experiment, with small head movements almost always accompanying gaze shifts in natural tasks.

The trajectories of the head movements were also variable. On some occasions the head appeared to follow the eye to the Model (as in Fig. 9a), or to move more or less directly between pickup and putdown locations with the hand (Fig. 9b, c). This flexible relation between eye and head movements suggests that the coupling between eye and head is less tight than frequently supposed. When the head goes with the eye, eye and head movements are probably initiated by a common gaze signal in body-centered or exocentric (spatial) coordinates, as postulated in a number of models of gaze (Guitton 1992; van der Steen 1992). In experiments in monkey with the head unrestrained, Freedman et al. (1996) have found that electrical stimulation of the superior colliculus elicits both eye and head movements consistent with the idea that these cells code desired gaze displacement. However, they have also found that the eye and head movements exhibit a degree of independence that requires them to postulate that the eye and head movements are controlled downstream of the superior colliculus by separate control mechanisms that take into account the position of the eye in the orbit. Tweed et al. (1995) reach the same conclusion in observations of human gaze shifts. The dissociation of eye and head trajectories observed here also requires separate controllers. In the present experiments, eye and head appeared to move toward spatially separate goals. This could occur in two different ways. One is that the two saccades and the diagonal head movement may be programmed independently to different locations. Another possibility is that eye and head are in fact programmed to the same final gaze location for block placement, but that the two eye movements are preprogrammed as a sequence. This would support Zingale and Kowler's (1987) suggestion that such preprogrammed sequences may be useful, because they facilitate the coordination of saccadic eye movements with other concurrent voluntary movements.

In most psychophysical experiments, gaze movements to single targets have indicated that eye and head are strongly coupled, despite flexibility in the relative timing and relative contribution of each to the gaze change (see review by Ron and Berthoz 1991), and a recent investigation of unrestricted gaze changes during driving also supports a common gaze signal (Land 1992). However, Ron and Berthoz have found some dissociation of eye and head with closely spaced pulse-step targets in opposite directions. More recently Kowler et al. (1992) have observed eye and head movements during reading, which go in the opposite direction at the end of a line of text, with the head moving left and down to the next line of text as the eye makes a final saccade to the right. (A similar instance of eye and head moving in opposite directions can be observed in Fig. 3, between 6,000 and 6,200 ms.) It seems likely that the current behavioral context is the primary determinant of the extent of coupling of eye and head. In many cases, such as Land's driving task, there is no clear advantage to a temporal dissociation between eye and head movements and, as Kowler et al. (1992) conclude, there is a natural tendency to program common eye and head movements. However, in the present task, the location of the Resource and Workspace are well known and a direct head movement is the most efficient strategy, given the slower speed of the head. Thus the widely diverging trajectories of eye and head observed in our experiments suggest that dissociation of the eye and head may be a common occurrence in natural movements.

Eye-head latencies were also influenced by the local task context in this experiment. When the head moved with the eye, it departed within about 50 ms of the eye. When a diagonal movement was made, the head began to move toward the Resource or Workspace about halfway through the Model fixation (about 200 ms before the eye movement to Resource or Workspace). This implies that the head movement does not wait for the eye in these instances, whereas the hand does. This is probably a consequence of their different roles. The hand requires a well-defined target, whereas the head does not. Presumably the primary requirement for the head is to keep the eye approximately centered in the orbit where the orbital position of the eye is most accurately known (Biguer et al. 1985), but a wide range of eye positions in the orbit are clearly used. Subjects sometimes made only very small head movements (a few degrees, for a 15° gaze change), and varied considerably from session to session. Since the head movement sometimes preceded the eye movement by 200 ms, the predictability of the next gaze change affected the timing of the head movement in this task. A similar effect of target predictability has been observed previously, although the head lead time is usually less than 100 ms. (Fuller 1992; Guitton and Volle 1987; Zangemeister and Stark 1982). Thus the eye-head system is very flexible when the timing and goals of the movements are under the subject's control.

When the head moved diagonally between Workspace and Resource, its trajectory resembled that of the hand. What is the nature of the relationship between head and hand? The relationship between hand and head movements has been examined in more detail by Smeets et al. (1996). They found that peak velocity and latency of the head covaried with that of the hand, when comparing movements made by subjects when they were instructed to touch the blocks with those made when they were placing the blocks in the same spatial arrangement. One interpretation of this is that a temporary synergy between the head and the hand is created to regulate the cycle of movements made in copying a single block. Ordinarily, the coupling of eye and head form a natural synergy. The trajectory variation in the present experiment may reflect the combined effect of eye and hand programming. That is, the variety of head trajectories may be generated by differences in the relative influence or relative timing of the eye and hand targeting commands. If the targets are coded as the forces required at the end point of the movement (as in equilibrium point models; Bizzi et al. 1984), the head trajectory might simply reflect the additive effect of these forces. It is efficient to link the head with either the eye or the hand in order to avoid having another control variable. A synergy with the hand might have developed in this experiment, because hand and head both alternated between the pickup and putdown in a highly predictable manner.

Conclusions

We observed the coordination of unrestricted eye, head, and hand movements during performance of a block-copying task. The task involved acquisition of visual information from the block pattern, alternating with visually guided hand movements for block pickup and placement. Observers took advantage of the repetetive nature of the task to generate stable but context-specific coordination patterns. The stable pattern of eye, head, and hand coordination probably resulted from the creation of temporary synergies or coordinative structures. Coordination of eye and hand movements was preserved by initiating the hand movement at about the same time as the eye movement to guide pickup and placement. This meant that hand movements were delayed when an information-gathering fixation was interposed, until the fixation was almost complete. This suggests that the eye and hand movements were treated as a temporary synergy in order to maintain coordination for pickup and placement. Maintaining a fixed timing between eye and hand was probably most critical for having the eye available for visual guidance of the final phase of the movement, rather than for initial targeting. Head movement trajectories were quite variable between and within subjects and frequently diverged widely from the eye trajectory. The head movements reflected the additional influence of either the concurrent hand movement or the final gaze target. Thus the link between the head and the eye in gaze changes was very much weaker than has usually been observed and is best represented as a commonly useful synergy rather than a tightly coupled movement pattern.

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